On the Development of a Coupled Land Surface and Groundwater Model

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Management of surface water quality is often complicated by interactions between surface water and groundwater. Traditional Land-Surface Models (LSM) used for numerical weather prediction, climate projection, and as inputs to water management decision support systems, do not treat the lower boundary in a fully process-based fashion. LSMs have evolved from a leaky bucket to more sophisticated land surface water and energy budgets that typically have a so-called basement term to depict the bottom model layer exchange with deeper aquifers. Nevertheless, the LSM lower boundary is often assumed zero flux or the soil moisture content is set to a constant value; an approach that while mass conservative, ignores processes that can alter surface fluxes, runoff, and water quantity and quality. Conversely, models for saturated and unsaturated water flow, while addressing important features such as subsurface heterogeneity and three-dimensional flow, often have overly simplified upper boundary conditions that ignore soil heating, runoff, snow and root-zone uptake. In the present study, a state-of-the-art LSM (CLM) and a variably-saturated groundwater model (ParFlow) have been coupled as a single column model.

An initial set of simulations based on data from the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) and synthetic data demonstrate the temporal dynamics of both of the coupled models. Changes in soil moisture and movement of the water table are used as indicators of conservation of mass between the two models. Sensitivity studies demonstrate the affect of precipitation, evapotranspiration, radiation, subsurface geology and heterogeneity on predicted watershed flow. Studies demonstrating the effects of watershed flow in uncoupled and coupled modes are presented. The coupled model will ultimately be used to assist in the development of Total Maximum Daily Loads (TMDLs- a surface water quality standard) for a number of pollutants in an urban watershed in Southern California in the United States.

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1. Introduction

Early climate simulation models assumed land surface hydrology to be a leaky bucket parameterization, and used this for the land surface lower boundary condition to atmospheric processes [1]. Such a simplistic description for land surface processes in Global Climate Models (GCMs) led to the development of Land Surface Models (LSMs) that include surface resistance, vegetation, and snow schemes that provide momentum, heat, an moisture fluxes to the lower atmosphere. (e.g.[2,3]). This was followed by LSMs with improved representations of ground hydrology, soil moisture movement, and evapotranspiration [4], and continental scale river routing [5]. At about this time, regional climate modeling with similar LSMs began to provide higher spatial resolution [6,7]. These regional climate models are based on numerical weather prediction models coupled with global climate model LSMs. More recently, detailed descriptions of surface infiltration and lateral baseflow have been developed [8–10]. The most recent LSMs [11] have advanced to include more detailed ecological and biogeochemical processes. However, all LSMs to date have a parameterization at the bottom layer that is either specified or fluxed to a representation of the overlying moisture gradient. Hence, the development of a new drainage flux term at the bottom layer has been proposed. The dynamics of this term hinges on the interactions between the upper layers, that is the LSM, and a deep layer ground water model (GWM).

Since about 1985, climate and hydrologic modelers began to discuss common problems, each bringing different perspectives. During the last decade, hydrometeorology evolved as a new field of study that merged these two disciplines. Detailed, fine scale descriptions of surface hydrologic concepts began to emerge in regional scale and global scale climate models, primarily in the form of parameterizations.

The purpose for such a coupled LSM and GWM is to determine the sensitivity of the water table to changing climate variables, the impact of the GWM on the LSM, and in turn the surface to atmosphere fluxes. Finally, a coupled LSM-GWM will help to better understand groundwater and surface water interactions at a range of scales and its effects on water quality.

In the following section we present an approach toward developing a coupled LSM-GWM, followed by a discussion of simulation and results, and finally summary and concluding remarks.

2. Models

2.1. The Common Land Model: CLM-hybrid

For the purposes of coupling we chose the model CLM-hybrid [12]. CLM-hybrid is a soil-snow-vegetation biogeochemical model. It is based on Land Surface Models developed by [2,13,11]. Each grid is partitioned into multiple sub-grids that define land characterizations at fine spatial resolution, while providing computational efficiency. Each grid can be subdivided into any number of subgrids that contain a single land cover type, including the dominant vegetation type, secondary, bare soil, wetland, lake, and urban (impermeable). It has a single vegetation canopy layer, 10 unevenly spaced soil layers, and up to 5 snow layers. Vegetation processes are a function of plant function types that are specified by optical, morphological, and physiological properties. The time varying parameters include the stem and leaf area indices, and the fractional vegetation cover. CLM can be either forced by observed atmospheric conditions or coupled to an atmospheric model, and requires atmospheric lower boundary input temperature, pressure, winds, precipitation rate, radiation (downward longwave, incident solar direct and diffuse), water vapor, observational height for air humidity, temperature, and winds. The prognostic variables are the canopy temperature, snow temperature, canopy water, snow depth, snow water equivalent, and soil moisture content.

2.2. ParFlow

ParFlow is a groundwater flow code developed at LLNL [14]. It solves for steady-state, fully saturated flow using a parallel, multigrid-preconditioned conjugate gradient solver or for transient, variably-saturated flow using a parallel, globalized Newton method coupled to the multigrid-preconditioned conjugate gradient solver. Both methods provide a very robust solution of pressure in the subsurface and excellent parallel scaling [14,15]. For this paper we are using the variably-saturated mode of ParFlow, which solves the mixed-form of the Richards equation [16]. Both the saturation-pressure and relative permeability-saturation functions are represented by the Van Genuchten relationships

2.3. Coupled Model CLM.PF

The CLM and Parflow models were coupled at the land surface and soil column with ParFlow essentially replacing the soil column/root zone formulation in CLM. A schematic of this couple is shown in Figure 1. As this figure shows, these models communicate over the root-zone via a series of ten soil layers. In the coupled model, infiltration, evaporation and root uptake fluxes are still calculated by CLM. These fluxes are passed to the upper ten soil layers in ParFlow where they are treated as water-fluxes into or out of the model. Pressure is calculated over the entire domain for the given timestep. Soil saturation is then calculated from the pressure solution and saturation profiles for the upper ten nodes calculated are then passed back to CLM. The model is fully-coupled at every timestep which is specified by the meteorological forcing. Soil temperatures, heat fluxes and energy balances are calculated by CLM.

3. Simulations and Results

3.1. Initial Simulations Based on Synthetic Data

To test the coupled model a simple simulation was undertaken designed to stress the boundaries of the two components. A so-called massive infiltration scenario was used to test the ability of the coupled model to balance water during flooding and dryout. This scenario simulated steady rainfall at a rate of .01 mm/s with no solar for 14 days. After 14 days the rain was turned off and incident solar radiation was increased to a rate of 150 W/m^2 and dryout simulated for 36 days. During the simulation, temperature, humidity and wind velocity are held constant at ambient conditions. Both CLM and the coupled model, CLM.PF were run under these conditions.

Figure 2 shows a plot of the results of this simulation for the coupled CLM.PF model. In this figure two key forcing parameters, precipitation and incident solar radiation are plotted with runoff and infiltration. Directly below this plot the entire time series of the saturation profile is plotted. In both plots time is displayed on a log scale. Figure 3

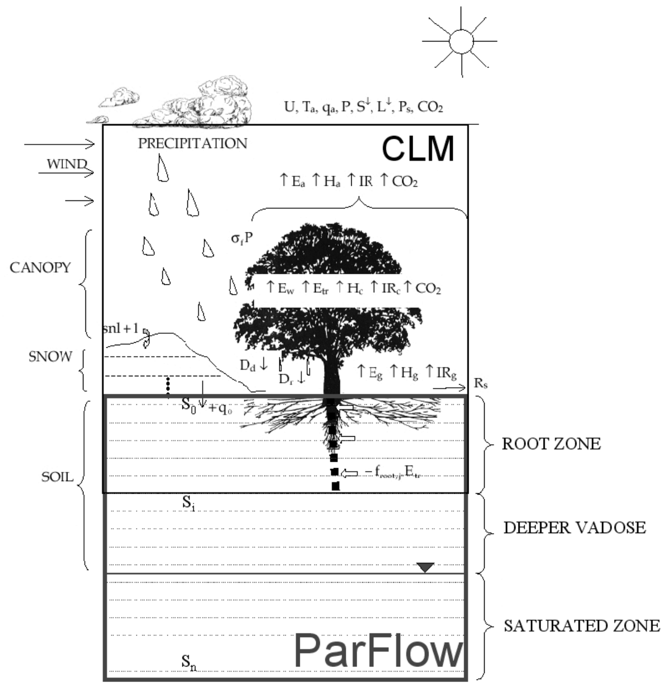

Figure 1. Schematic of coupled Land Surface-Groundwater model.

plots the same atmospheric forcing and model response for the CLM model. Note the difference in depth below ground surface represented by these two models as presented in these figures; CLM simulates to a depth of 2m and CLM.PF simulates to a depth of 10m.

Inspection of Figure 2 clearly shows the coupled models response to the steady infiltration. Infiltration starts almost immediately with the onset of precipitation and initially represents a large fraction of the surface water balance.The infiltration front can be seen as it advances towards the water table; which after three days of steady infiltration advances towards the ground surface. As the soil column fills with water the infiltration is moderated and runoff increases. At approximately 5 days the model has completely flooded and infiltration shuts off entirely with all of the precipitation resulting as runoff (as overland flow). Once the precipitation has ceased and the incident solar radiation is increased the coupled model slowly starts to dry out. At the end of the simulation the water table has receded slightly.

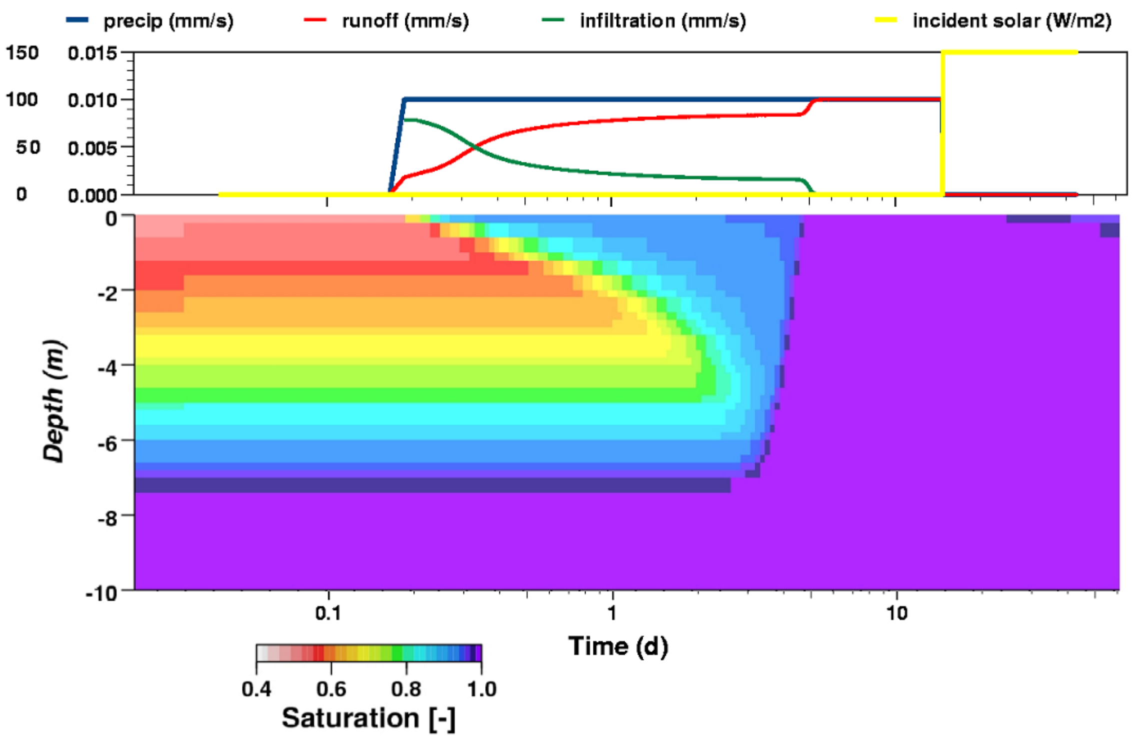

Figure 2. Plot of meteorological forcing, precipitation and incident solar radiation; and CLM.PF model results for runoff, infiltration and soil saturation with depth as a function of time for the massive infiltration synthetic simulation. Note the log scale for time in this picture.

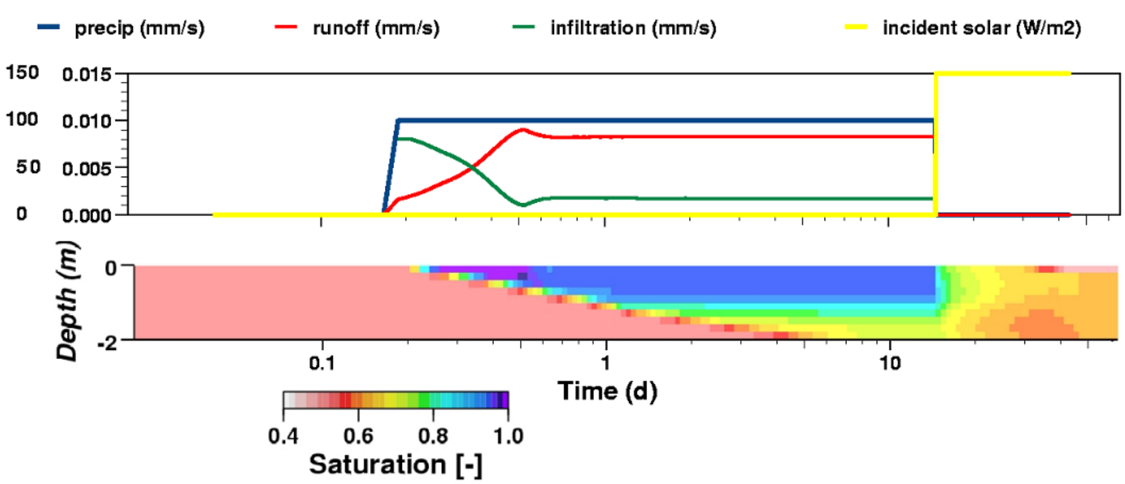

Figure 3. Plot of meteorological forcing, precipitation and incident solar radiation; and CLM model results for runoff, infiltration and soil saturation with depth as a function of time for the massive infiltration synthetic simulation. Note the log scale for time in this picture.

Figure 3 displays the response of CLM to steady infiltration. The very top layer of soil in the CLM model saturates rapidly causing a large balance of the precipitation to run off after a few hours of simulation time. The saturation front advances downward, reaches equilibrium within 10 days and the CLM model does not flood. Once the precipitation has ceased and the incident solar radiation is increased the CLM model dries out more rapidly than the coupled CLM.PF model. Comparison of Figures 2 and 3 highlights some of the differences between the CLM and coupled CLM.PF models; the addition of the deeper soil column and explicit representation of the water table and saturated zone has a pronounced affect on the response of water in the soil column.

3.2. Comparison to the Program to Intercompare Land-surface Process Schemes, Usadievsky Watershed, Valdai, Russia

In order to provide a more realistic comparison of the CLM and CLM.PF models, a realistic weather data set was used. A 46-day summer segment of the 18-year meteorologic forcing dataset from the Usadievsky watershed in Valdai, Russia was used for this purpose [17]. This data was used to drive both models using the same land-surface parameters and very similar descriptions of the subsurface. The results of the CLM.PF model response to this forcing data are displayed in Figure 3 and the results of the CLM model response to this data are displayed in Figure 4. This dataset was used only for comparison of the different models' predicted response of the subsurface; not to validate either model against observations at the Valdai site. Both models are in "spin-up" mode in this comparison similation and this is not meant to prove or disprove the validity of either model. Both models predict very similar response over the first 15 days of simulation time. During this time there is little rainfall and both models predict little infiltration into the subsurface with most of the precipitation being removed due to root uptake and evapotranspiration. After this time the model predictions of the subsurface diverge. The CLM.PF model predicts infiltration of rain-events into the deeper subsurface; the CLM model continues to remove the water by evapotranspiration. Towards the end of the 46-day simulation, the CLM.PF model predicts some change in the level of the water table, as the water infiltrated with each of the individual rainfall events migrates to the deeper saturated zone. The affect of the water table on the response of the subsurface can be clearly seen.

4. Conclusions

Coupling the land surface and groundwater models produces a model that behaves much differently than either model independently. This coupled model provides simulations of the subsurface, that because of the explicit accounting for water to and below the water table, have a memory of water stored in the deep subsurface. The preliminary simulations presented here show that this scheme balances mass across the LSM/GW boundary and may provide interesting insight into coupled processes.

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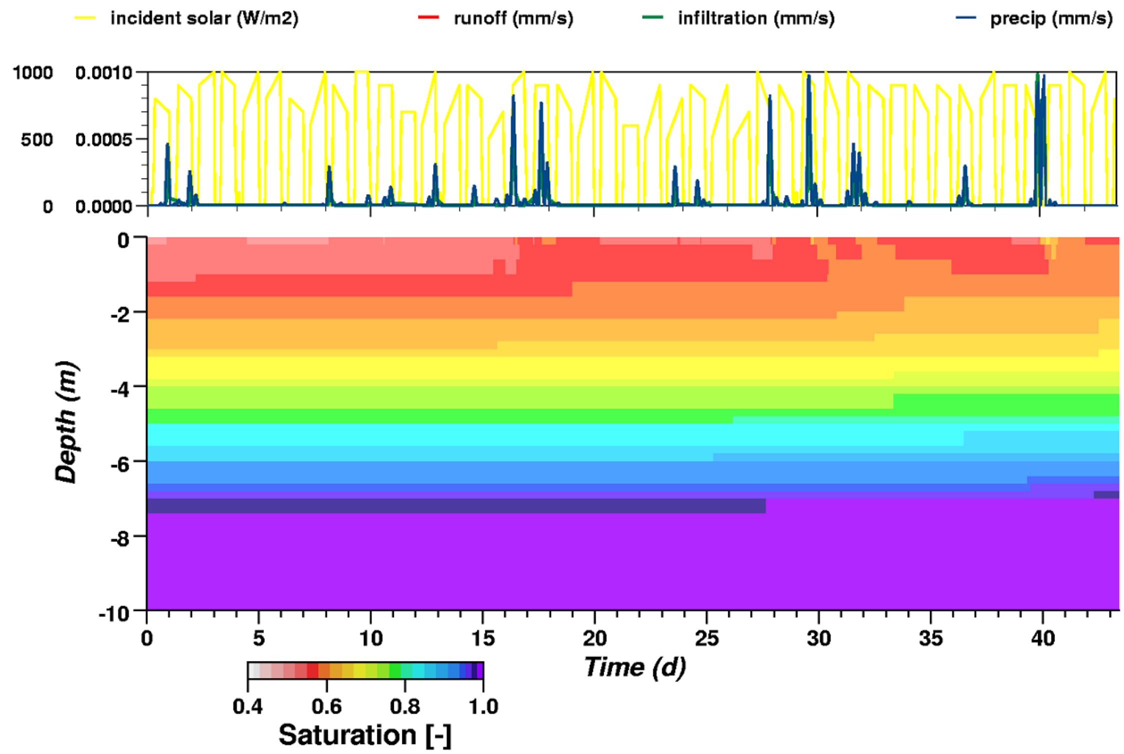

Figure 4. Plot of meteorological forcing, precipitation and incident solar radiation; and CLM.PF model results for runoff, infiltration and soil saturation with depth as a function of time for a 46-day time series of the Valdai dataset.

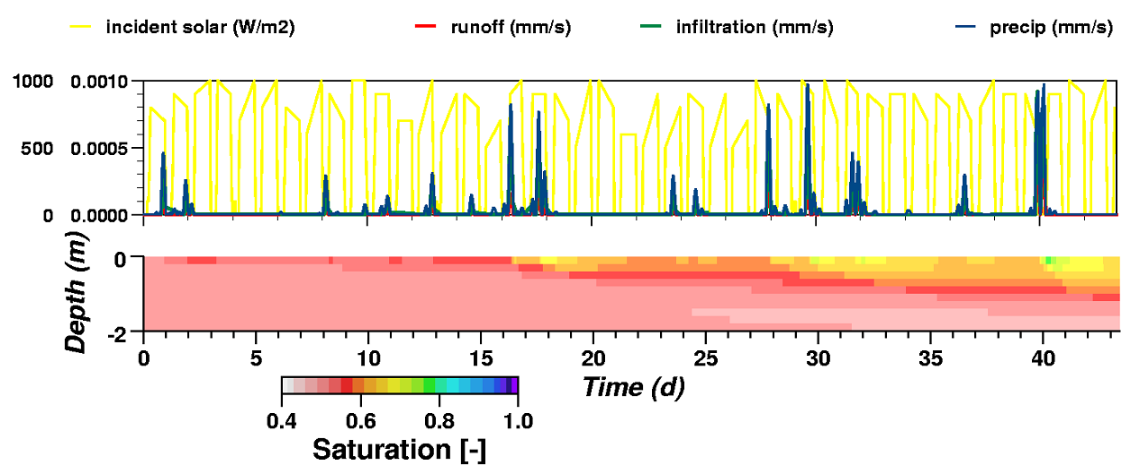

Figure 5. Plot of meteorological forcing, precipitation and incident solar radiation; and CLM model results for runoff, infiltration and soil saturation with depth as a function of time for a 46-day time series of the Valdai dataset.

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